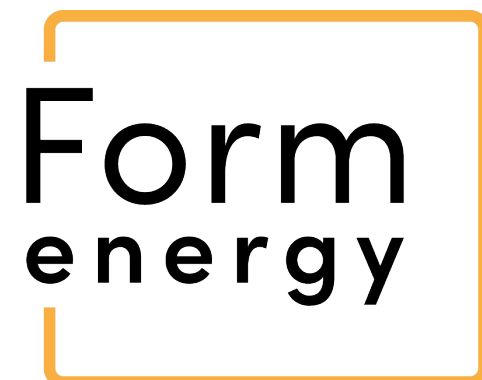


CHALLENGES AND OPPORTUNITIES FOR THERMOCHEMICAL REDUCTION OF IRON

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ARPA-E: Zero-emission Iron- and Steelmaking Workshop
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Energy Storage
For A Better World

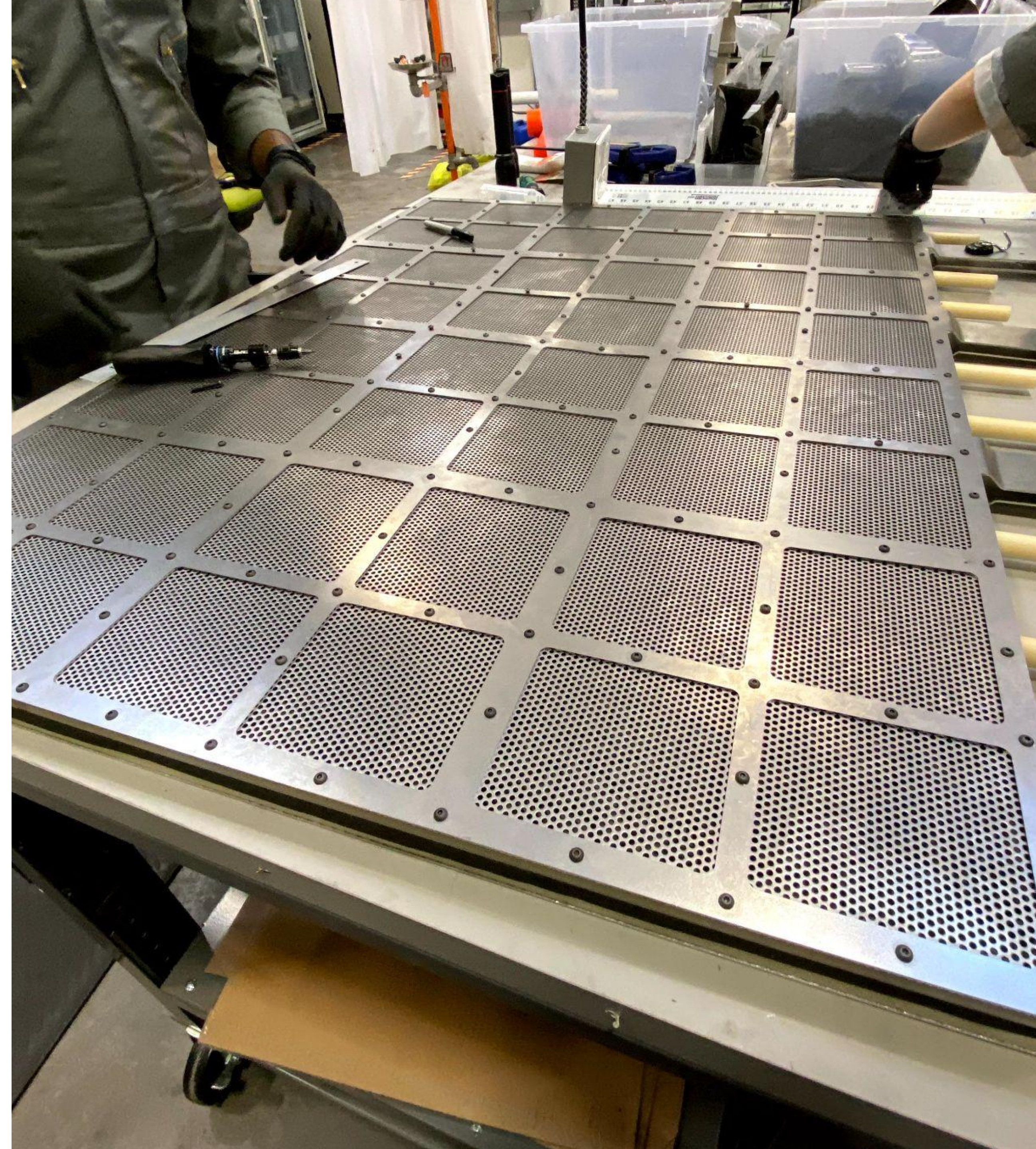
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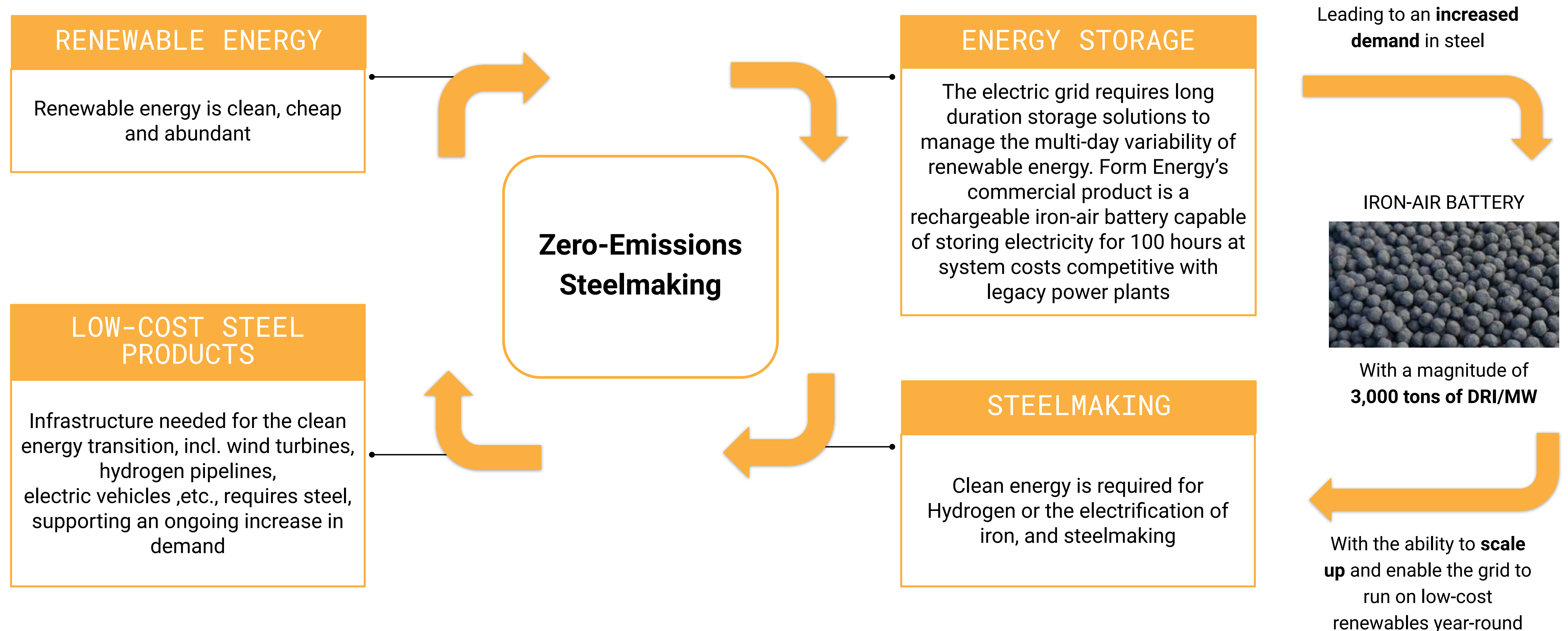


PIONEERING MULTI-DAY ENERGY STORAGE TECHNOLOGY

Our best-in-class team is composed of
passionate people who are deeply
motivated to create a better world



Multi-day storage is necessary to decarbonize steelmaking and a win/win for the steel industry



Iron-Air Batteries Can Mirror DOE's "Build Back Better" Agenda

Innovation in multi-day energy storage that inspires a new industry to speed decarbonization and create the U.S. clean energy economy that can:

- **Cut carbon emissions faster** while **reducing electric system costs** at the same time.
- Create home-grown **advanced manufacturing** that will **transform the U.S. electric grid** and **support domestic supply chains**.
- Realize the vision of **clean energy jobs** filled by **American workers**.

Thermochemical Iron Ore Reduction (alternatives to blast furnaces)

Historical Perspective

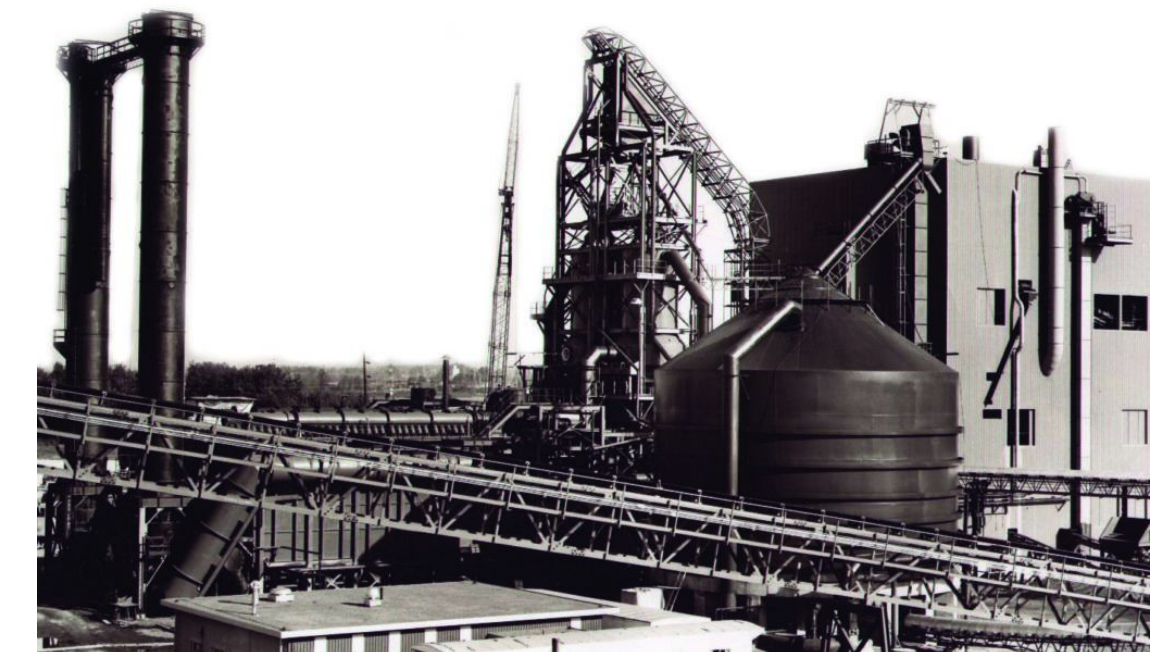
- **ca. 2000 BC:** first evidence of iron smelting in modern-day Turkey
 - **1200 BC:** beginning of the iron age
 - **1500s:** increasing temperature of ironmaking; molten pig iron
 - **1709:** use of coke (refined coal) due to deforestation in England from producing charcoal.
 - **1829:** Hot blast, considered to be the beginning of modern blast furnaces
- **1957:** Hylsa developed the first NG-based direct reduction process due to rising scrap prices
 - **1965:** Surface Combustion Division of Midland Ross Corp builds a 200 kg/h pilot plant in Toledo, OH
 - **1969:** Midland Ross Corp. starts a 150,000 t/y MIDREX plant in Portland, OR
 - Plant never reached design capacity and was eventually scrapped.
 - Process was re-designed for the next plant
- **1971:** Georgetown, SC and Hamburg, Germany: 400,000 t/y continuous discharge. Hamburg is still operational.
 - **2021:** 100+ DRI plants; >110Mt/y DRI



Washington Iron Furnace, Rocky Mount, VA ca. 1770



Carrie Blast Furnace, Homestead, PA 1881-1978



Oregon Steel Mills

Other (thermochemical) Ironmaking Processes

- Many processes have been invented to replace the blast furnace with cheaper energy and/or raw materials
- Only 2 have been commercially successful: Rotary Kilns and gas-based shaft furnaces, and only represents 7% of annual iron production
- Fastmet, Corex, Finmet, (ITmk3) survived the 'pilot' phase
- HYFOR, HiSarna and Tecnoled are still in 'pilot' phase
- Transition from Pilot to first commercial plant has historically been the demise of new process development

	Gas	Coal
Concentrate, Fines	Circored Iron Carbide Finmet / Finex HYFOR	Fastmet ITmk3 Tecnoled Circofer Primus Finex
Lump ore, Pellets, Sinter	Midrex HYL	Blast Furnace Rotary Kiln (SL/RN, DRC etc.) Corex Hismelt HiSarna Romelt

~70% of world iron production

~7% of world iron production:

~75% by shaft furnace

~25% by rotary kiln

Challenges & Opportunities: Business Environment

Timing:

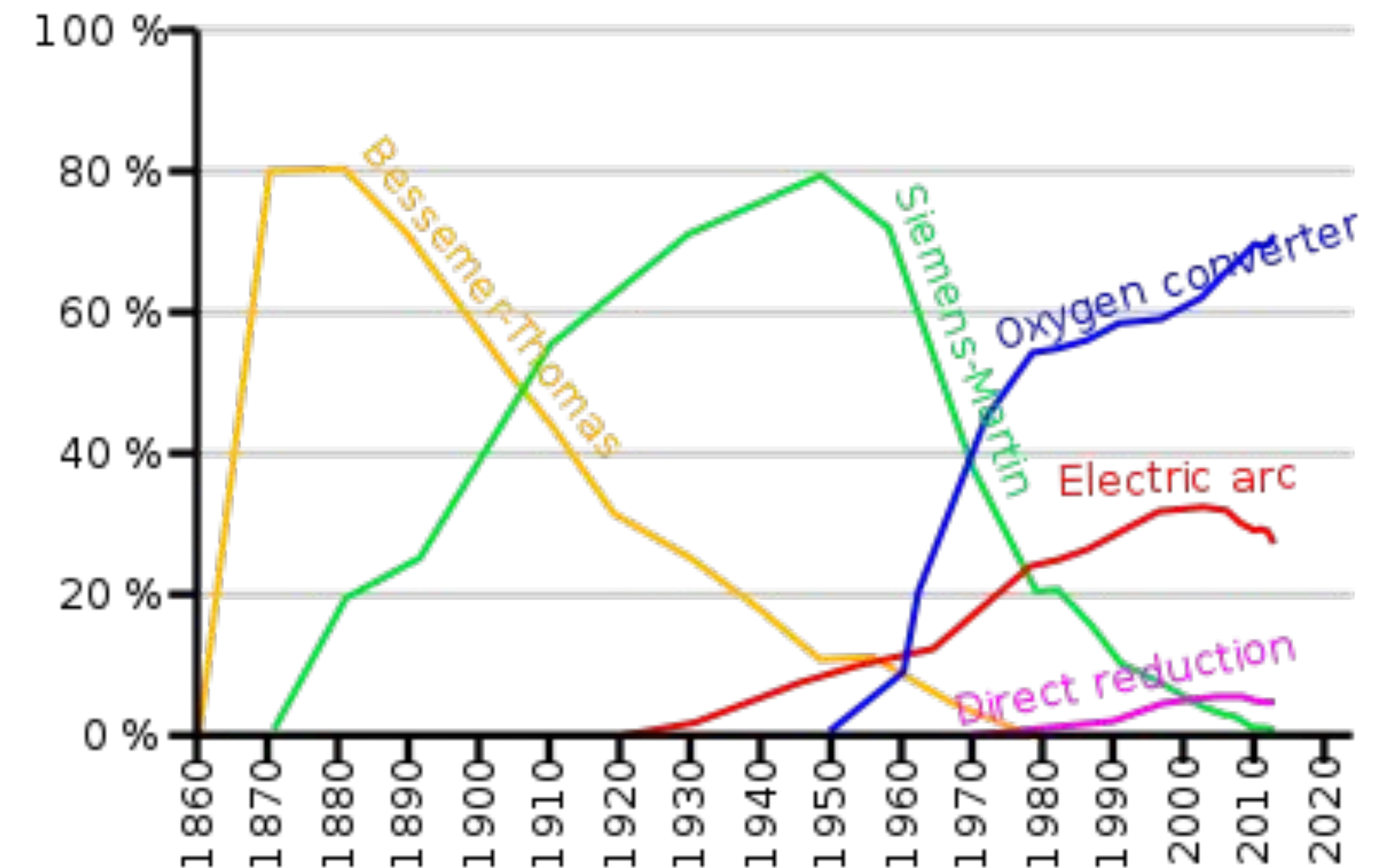
- Full technology conversion in steelmaking take time (Open hearth to BOF took 20 years)
- Compatible with 2040-2050 goals
- Switching one vessel is easier than the entire plant

Market:

- Steel products are low margins in highly competitive markets
- Steel products travel easily, with little geographical protection (besides import duties)
- Limited ability for the intermediate customers to absorb price increase

Capital costs:

- Steelmaking benefits from economies of scale
- Equipment is very capital intensive, and difficult to finance
 - Low ROI
 - New technologies are high risks
- Race to government subsidies



<https://en.wikipedia.org/wiki/Steelmaking>

Challenges & Opportunities: Energy

Carbon in ironmaking

- In steelmaking, carbon is used both as a molecule and as a source of chemical energy
 - Strongly exothermic 'in situ' chemical reactions $C + \frac{1}{2} O_2 = CO$ and $CO + \frac{1}{2} O_2 = CO_2$
 - Carbon lowers the melting point of iron
 - Protects re-oxidation of iron
- Necessary for physical properties of steel
- Replacing carbon by "something else" will most likely be less energy efficient; therefore it must be low-cost and abundant
- Carbon neutral, not carbon free; supply only absolutely required carbon from zero-emission sources

Electrification for Hydrogen generation

- Electrolysis requires green power (GHG emissions from power generation)
- Cost and availability of green hydrogen are the main limiting factors to deploy hydrogen in steelmaking
 - Who will get hydrogen allocations? Ideally the sector that reduces GHG the most, not the ones that can afford it most
 - Hydrogen storage and transport are expensive (pressure / temperature)
 - using ammonia as a carrier of hydrogen may require improvements in cracking technologies
 - better hydrogen carrier

Electrification for heating

- Electric-Arc Furnaces were designed to melt scrap; not ideal to melt other raw materials
- Induction is possible, but has limitations in vessel size
- Injection of hot gases, such as plasma heating or other efficient electrical heaters compatible with steelmaking duties (e.g. high reliability, low maintenance cost)

Carbon 'recycling'

- Carbon looping vs. carbon avoidance
 - Recycling CO_2 into graphitic carbon
- Biomass for use in BF, DR and Tecnoled:
 - Replacement of ethanol corn (for vehicle fuel) with other crop(s) better suited for steelmaking
 - Direct use of ethanol in steelmaking

Challenges & Opportunities: Raw Materials (iron)

Decarbonization of the mining industry

- Outside of this scope, but it is a necessary condition
- Production of iron at or near mine sites
 - Locally produced renewable energy. No need for co-location of natural resources
 - Shipping energy savings: shipping 30% less weight (Fe_2O_3 vs. Fe)

Iron Ore Selection

- Iron ore processing transforms a non-uniform product into a consistent, uniform intermediate material
 - Expensive, but difficult to eliminate
 - Mineral processing (upgrade of iron ore to higher Fe content) is difficult to eliminate since iron ore quality is declining
 - Pelletizing + induration facilitate transportation (yield)
 - Blending allows the expansion of material sources that can be used in supply chain
- Any process restrictions on raw material affects pricing and supply
- Any novel ironmaking processes must be adaptable to a wide range of iron ore
- Local vs. global iron ore production

Iron Ore to ironmaking optimization

- Supply-chain is currently optimized for BF and DR-grade iron ore
- New process(es) should adapt to existing raw materials, not impose restrictions
 - for example, use lower Fe content iron oxide
- Process efficiency: heat, material flow etc.
 - for example, hot charging indurated pellets in DR furnace
- What is the optimum intermediate product between mining and steelmaking? C, gangue, physical characteristics, transport, etc.

Challenges & Opportunities: (existing) process selection

- **Blast furnaces role in the transition to lower GHG emissions:**
 - The path to zero-emission must include BF improvements in the transition, but cannot reach zero emissions.
 - The blast furnace is an energy efficient and integrated process (one-step reduction+melting, in-situ energy, use of waste gases)
 - Assets are already depreciated, but require expensive relining every ~20 years
 - Raw material flexibility (e.g. Silica in iron ore)
 - There are many opportunities to reduce CO₂ emissions in the BF, such as increase use of pellets and HBI and using alternative fuels like natural gas, hydrogen and/or biomass
- **Direct Reduction (with Natural Gas and hydrogen) + EAF in the transition to lower GHG emissions:**
 - Already lower carbon footprint, can be transitioned to near (or net) zero emissions
 - High capital costs; require infrastructure for NG and later hydrogen
 - Tighter raw materials requirements (e.g. pellets, low silica iron ore)
 - Use of natural gas to produce external H₂ generally does not make sense
- **Carbon capture, use and storage**
 - Practical solution needed
- **Other processes with potential:**
 - Tecored with biomass - Vale is engineering the first commercial plant
 - Circored 2.0 with external green hydrogen
 - Flash Ironmaking - ready for first commercial plant?
 - HYFOR
 - Direct Electrolysis

Challenges & Opportunities: (new) process selection

- **New electrified ironmaking process(es)**

- Electrification can be direct or indirect, or a combination of both
- co-location with mines or steelmaking operations to benefit from energy and infrastructure synergies
- Continuous process is generally preferred over batch
- Must be able to scale in 3D (capex increases at a factor of $\frac{2}{3}$ vs. 1 for 2D scale up)
-

- **New melting vessels**

- Rethink how liquid iron, scrap, HBI etc. should be melted, instead of adapting EAF, smelters etc. that were designed for other / limited purposes
- Watch for emissions boundaries (decarbonizing one step by increasing emissions in another) and claims of 'easy' carbon capture

- **Risks and Finance**

- Pilot / Demonstration plant can lower risks, but will not eliminate *all* risks
 - Mass and Energy balances (and therefore OPEX) are challenging to extrapolate to large scale operation
 - CAPEX is difficult to extrapolate precisely without detailed engineering, which can't be done without a financed project
- Scaling up success has been in the 7x - 15x
- Must be allowed to learn from mistakes, but maintain focus on 'death-threats' (i.e. solve the hard questions first)

⇒ Paradigm change is needed for financing the scale up needs (high risks, low returns)

Thank you!